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## PROPOSITION DE SUJET DE THESE

**Intitulé:** The Bi-O Edge sensor: a new concept of ultra sensitive Wave-Front Sensor dedicated to exo-earth characterization

Référence: **PHY-DOTA-2024-17**
*(à rappeler dans toute correspondance)*

| **Début de la thèse :** 01/10/2024 | **Date limite de candidature :** 01/05/2024 |
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**Mots clés :**

Astronomical Telescope, Adaptive optics, Fourier Filtered Wavefront Sensor, Super-Resolution, on-Sky, Validation, extrasolar Planet, High Angular Resolution

**Profil et compétences recherchées :**

Engineering school of Optics, Master in Astronomy, Optics, Physics

**Présentation du projet doctoral, contexte et objectif :**

**Context:** Adaptive Optics (AO) has become a key technology for ground-based astronomy to compensate for the effects of the atmospheric turbulence. Most of the 8 to 10 m diameter class telescopes are now equipped with AO system that offer very high levels of performance and reliability. The never-ending request for higher precision has led to develop eXtreme AO (XAO) that aims at reaching the ultimate AO performance toward the discovery and characterisation of new worlds.

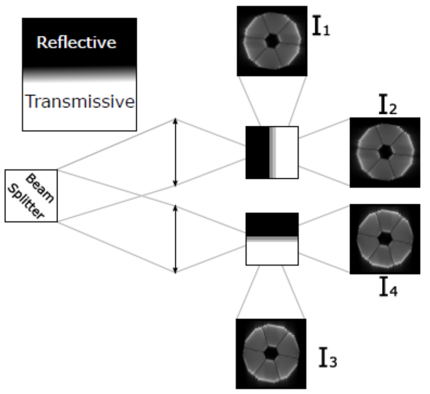
An XAO system combines (i) a high actuator count deformable mirrors (DM), (ii) a very high resolution and sensitivity wave-front sensor (WFS) and (iii) very fast real-time algorithms. For example, the SAXO instrument, developed by ONERA [1], is installed at the ESO Very Large Telescope in Chile provided the AO correction at 1,5 kHz to obtain the first ever image of a multi-planet system around a Sun-like star.

Today, the Astronomical community is looking forward the advent of the next generation of Extremely Large Telescopes (ELT) that promises to reach very high sensitivity and angular resolution thanks to their unprecedented collecting area [2]. The astronomical instruments will rely on state-of-the-art AO instrumentation that will face stronger disturbance than ever before, sometime originating from the telescope itself.

One of the most attractive science cases of the future ELTs will be to directly image **rocky exoplanets, close to their host star** to characterize **the spectral composition of their atmosphere**. The eventual discovery of oxygen lines would indeed shed light on complex planet formation mechanisms and be a crucial milestone towards the first detection of another form of life in our Universe. However, this ambitious goal will rely on very high-performance AO systems (down to a nanometric precision) to provide the adequate contrast and distinguish the very faint planet from the very bright star.

The challenging environment of the ELT and the high precision targeted for astronomical observation call for **the development of new wave-front concepts and innovative control strategies** to benefit fully from the ELT angular resolution**.**

To address this hunt for sensitivity, the AO community has been actively investigating an innovative type of WFS, the Fourier-Filtering WFS (FFWFS) that can potentially reach the theoretical maximum sensitivity [3]. In this context, **a new concept, the Bi-O Edge WFS, has been proposed and specifically designed to meet the requirements of XAO systems** [4].




*Optical layout of the Grey Bio-Edge WFS. The grey color denotes a gradient-like semi-reflective zone [4].*

This new WFS combines the formalism of the FFWFS and the concept of super-resolution applied to the wave-front sensing [5] to maximize the sensitivity of the system while keeping a large dynamic, making it a serious candidate for the future XAO systems that will equip the ELT [6].

**The goal of this thesis is to bring this new concept in operation, investigating the feasibility of the concept as well as its optimisation.**

**Objectives**

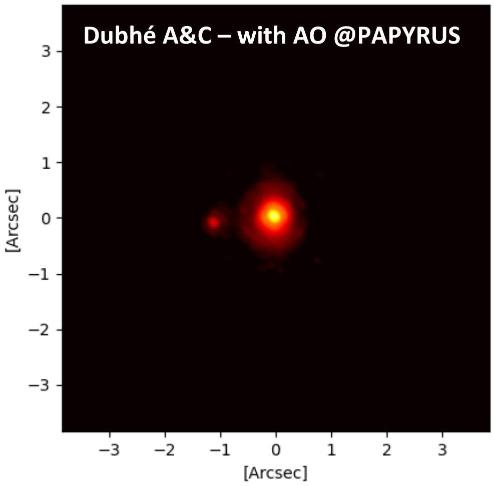
The Bio-Edge WFS has been developed making use of a theoretical formalism describing the FFWFS developed at LAM to predict its performances in terms of sensitivity [7]. Two variants of Bio-Edge have been derived, one revisiting the concept of Foucault Knife Edge (Sharp Bio-Edge) and a second one, more innovative, making use of semi-reflective materials to remove the need of Tip/Tilt modulation (Grey Bio-Edge). The general concept has been validated in end-to-end simulation using a typical ELT AO system. It exhibits very promising results, **with almost a factor 2 of gain** in sensitivity with respect to a modulated pyramid WFS (considered as a reference by the AO community).

**The next step consists in taking this attractive theoretical concept to the next level and validate it experimentally**. It will be necessary to evaluate the feasibility of the current design (non common aberrations between the different channels? manufacturing of the optical mask? compacity?). It is expected that the Bio-Edge will suffer from non-linear effects that must be properly (i) characterized (ii) monitored and (iii) compensated, eventually using additional devices such as a Gain Sensing Camera (GSC) [8].

The performances of the Bio-Edge will have to be challenged against the current state of the art in terms of FF-WFS: the pyramid WFS. To that end, the LAM and ONERA have developed a variety of tools that will be very pertinent to carry on the work: semi-analytical models [7] and end-to-end AO simulation tools, developed in-house [11], [12].

The super-resolution capabilities predicted by the design of the sensor have not been fully studied nor demonstrated yet. This concept originates from the redundancy of the information in the WFS signals: by adding a known diversity, it is possible to increase significantly the spatial frequencies properly seen by the sensor. **This will result in an increase of the overall performance and could be a crucial asset for the sensing of new types telescope disturbances such as Pupil Fragmentation and Low-Wind Effect.**

In this context, LAM and ONERA provides a direct access to an AO facility unique in Europe, combining both laboratory (LOOPS) and on-sky (Papyrus) benches to test new ideas and new components developed for the next generation of AO systems. The LOOPS bench has been used intensively in the LAM premises for more than 5 years now and has demonstrated its ability to trigger and support the development of brand-new concepts [9]. In addition to LOOPS, after a first light obtained in 2022, the PAPYRUS bench is now fully operational and offers stable performances to provide a direct access to the sky and experiment/validate new ideas.



*Binary Star Dubhé A&C imaged in the visible with PAPYRUS.*

The thesis objectives are the following:

1) Characterization of the Bio-Edge WFS (sensitivity, dynamics) using the LAM/ONERA numerical tools to compare its performances to existing and well known WFS (Pyramid, Zernike WFS).
2) Tuning of the design to maximize the performances in presence of Kolomogorov and non-Kolomogorov disturbances (pupil fragmentation, low-wind effect) making use of the super-resolution concept.
3) Proposition of a design and manufacturing of a prototype of Bio-Edge (grey variant).
4) Validation and characterization of the prototype on the LOOPS bench at LAM and/or the GHOST bench at ESO [15].
5) On-sky demonstration using the LAM/ONERA PAPYRUS platform and eventual coupling with a GSC.

The student will build on the developments already carried out by the LAM-ONERA team in the context of SPHERE-SAXO [1] development for the VLT and the dimensioning phases of the ELT projects (in particular the HARMONI [13] instrument and its AO suite (see https://www.lam.fr/projets-plateformes/projets-sol-et-spatiaux/article/e-elt-harmoni). Both of them have allowed a fine description and a complete understanding of the problem of extreme AO correction for extrasolar planet direct imaging. Improving the solutions already proposed for the VLT and ELT instruments, or proposing alternative concepts, will be of importance for all future astronomical instruments.
The proposed developments will naturally be used for the High Contrast mode of the HARMONI project [14] but can be extended to the future Planet Finder system AO that will see the light of day in the next two

decades (SPHERE+, and RISTRETTO projects on the VLT, ANDES and PCS on the ELT to quote only the principal ones).
In this context, it is scheduled to actively collaborate with the AO group at the ESO in Garching as this concept is central to the development of PCS [6]. Short- or/and long-term visits to ESO are envisioned to make use of the GHOST bench and collaborate with the other developers of the concept.

It is also important to note that this development will be extremely important for the development of the new generation of Space Situational Awareness [SSA] system for identification and the follow up of Low Earth Orbit [LEO] Satellite or for the study of the close vicinity of Geostationary [GEO] Satellites (detection of small "spy" satellite or thread). Such applications will require accurate, very fast (few thousand of Hz) and very sensitive (low flux regime) wave-front sensors. A Super-Resolved FFWFS will be a promising solution for being integrated in the future ONERA SSA observatory.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**Collaborations envisages:**

European Southern Observatory, Arcetri Observatory, IPAG


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